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Thermodynamic analysis of compressed air energy storage working conditions

The compressed air energy storage (CAES) technology and electricity generation by this system are described. General performances and possible system efficiency definitions of those kinds of systems are indicated. Hybrid systems which consist of CAES and other renewable technologies (RT), e.g., wind turbines, are presented. A possibility of CAES-RT location in Poland is indicated. Dynamic mathematical model of CAES is presented; using this model the results for compressing and expanding operating modes are obtained.

1 Introduction

For obvious reasons the energy load on the grid is variable in time. There are both short-term variations within a day and long-time variations of seasonal character. The variability of load is further increased with connection of the sources characterized by low reliability. Sometimes it poses a significant risk of high output changes resulting from factors independent from the load changes. This applies primarily to wind turbines and also solar power stations.

One of the methods of supplying peak-load energy is to use various forms of energy accumulation. Classic solutions involving such accumulation capabilities are:

- pumped-storage power plants;
- compressed air energy storage (CAES) power plants, which use decompression of air stored in underground accumulators (reservoirs).

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The latter technology has been introduced quite a long time ago (Huntorf Power Station of 280 MW, Germany 1978 [1,2].) Until now one more large installation of this type has been commissioned (Mc Intosh, 110 MW, USA, 1991); there are several experimental plants as well. There is also a number of plans for such projects even of very high outputs (the largest being the Electric Power Generating Facility in Norton, total plans for 2700 MW based on CAES units with 300 MW turbines), however their construction is still being delayed. Bearing in mind the future of the renewable energy sources, it is interesting how these can cooperate with CAES plants – such projects are described further: CAES plant in the world, realized and planed:

- Huntorf, Germany – the first commercial CAES (290 MW)
- Mc Intosh, USA (110 MW)
- Norton, USA (finally is planed 2700 MW) – declared in the literature to be built in phases, in 2010 the project has been sold to a big energy company – First Energy – construction is to be launched in 2011
- Markham, Texas, USA (4×135 MW = 540 MW)
- Dallas Center, Iowa, USA (cooperation with wind turbines was planned – finally project is terminated because of inadequate geological conditions *in-situ*)
- Sestra, Italy (25 MW) – experimental power plant in which air is stored in aquifer, probably not involved any more
- Vianden, Luxemburg (285 MW)
- Ll. Torup, Denmark
- Some data can be found for: Japan (35 MW), Israel (3×100 MW = 300 MW – Israel Electric Company), Russia (1050 MW), Korea (300 MW), and Morocco (400 MW)

In Poland there are convenient locations for the construction of CAES. Knowledge of this technology is not widespread (virtually none.) Additionally, there is very lack responce from the power industry.

A working concept of a CAES power station is presented in Fig. 1. More complex configurations of such installations are described for instance in [3,4]. Compressed air can be used for smaller application in similar way [5]. This type

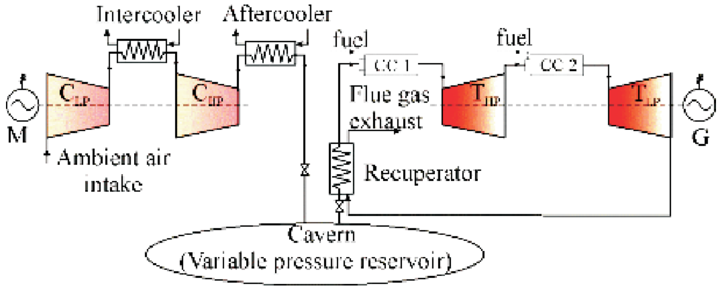

Figure 1. Working principle and main elements of the CAES power station used for peak-load generation – separate compressor drive and power generation equipment: CLP – low pressure compressor, CHP – high pressure compressor, CC1, CC2 – combustion chambers, THP – high pressure turbine, TLP – low pressure turbine, M – motor, G – generator.

of plant consumes cheap electricity – available while the load on the grid is lower – for instance at nights and during weekends. This power is used to compress the air inside the great containers. Accumulation of the compressed air is based on experience – also Polish – with the underground natural gas storage, which trace 60 years back. Due to huge volumes of required air and resulting financial restrictions currently it is only economically feasible to use natural reservoirs. They can be for instance salt caverns, aquifers and excavations in salt, limestone and other mines created within the hard rock structure.

Due to a volume of storage spaces, even those large, the storage pressure must be relatively high. The maximum value should be considerably higher than the required level for the installed combustion chamber within the gas turbine unit. The minimum value in the storage cycle should also exceed the level required for the combustion chamber. The generation is started up when the demand for electricity is high. The air is discharged from the accumulating space and decompressed in the turbine. Due to high compression ratio of the compressor, resulting from the requirements mentioned above, it is necessary to use intercooling in such a plant (which is not marked in Fig. 1). Additionally it is required to keep appropriately low temperature of the air fed into the storage (inter-coolers and an after-cooler after the last stage of the compressor).

An advantage of the CAES concept is the fact, that – as opposed to the situation when the fuel gas is stored – the gas turbine can work independently during the decompression process. Thanks to that the power transmitted to the generator is not limited by the necessity to drive the compressor at the same time. In the power balance of a classic large gas turbine unit (compressor-combustion chamber-turbine) the compressor drive requires more than 50% of the power generated in the turbine. Separation of the compression and decompression in time allows the turbine to deliver much higher output then required to drive the compressor in the classic scheme. Ability to carry out the compression process in longer period allows to further increase the difference in power consumed (by the compressor) and delivered (by the turbine).

The CAES systems should not be treated as a ‘pure’ method of storing the energy, as they consume fuel supplied to the gas turbine unit. In this situation they should rather be considered hybrid systems used both for generation and storage of energy. Their significant features are ability of quick ramp-up and favorable ratio between the power output and power demand for compression. The air from the storage can be decompressed without any fuel input, but the energy effect in this case is relatively smaller, and the output air temperature lower than the ambient temperature. The air fed into the turbine can be warmed up in a heat exchanger (Fig. 1), by the heat recovered from the exhaust gas and then used in the combustion chamber. Additional option is to use the energy recovered in the cooling process before feeding the air into the cavern.

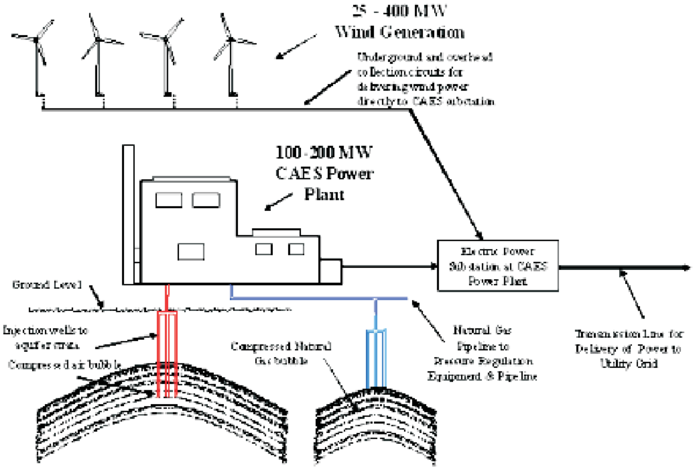

Figure 2. Scheme of the Iowa Stored Energy Plant, which illustrates the rules of cooperation with external objects, including a wind farm and underground gas and air storage [6].

2 CAES plants cooperating with RES, including wind turbines

One such installation was planned near Fort Dodge, Iowa (USA). It is planned to use an aquifer to store the compressed air there. A distinctive feature of this project is a plan to simultaneously store the natural gas in a similar way (Fig. 3). It is considered to store the gas and air in the same or (alternatively) various geological layers. Both possibilities have been identified at the planned site. It is considered to use the existing natural gas deposits as a 'cushion' to store the gas fed from the grid. This project is now in the phase of study works, cofinanced from the public money (Department of Energy). Similar projects were also considered in Europe (for instance L1.Torup in Denmark). Generally they would allow to store the energy generated by the Renewable Technologies, which as a rule work in irregular cycles, and use it to cover peaking load and provide daily balancing – or, if larger storage would be available, also for long-term balancing. The concept of CAES-wind farm cooperation is also discussed in [2].

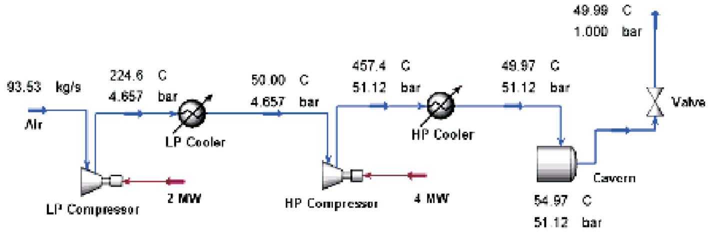

Figure 3. Scheme of the cavern charging process in the software used.

The Europe is currently one of the world's leading regions in development of wind power. This fast growth can be illustrated by the increase of the installed output of wind farms from 1600 MW in 1994 to approximately 48 GW in 2006. Against this background the wind power installed in Poland (280 MW in October 2007) seems very small, but there is significant interest in new projects. In Poland there are also possible sites allowing to construct CAES plants. Construction of such an installation could prove particularly interesting now – bearing in mind current conditions. For some time, due to rapid growth of the power demand, especially in the northern part of the national grid, some threats for the power supply security are indicated.

It is considered a primary solution for the mentioned problem to use peaking-load gas turbines. However a CAES plant has some advantages when compared to the classic gas turbine solution. It could accumulate the energy generated by renewable technologies and feed it to the grid during the high-load period. It also has a lower demand for the fuel gas when compared to the power output (which stands for smaller gas connection needed). Primary difficulties are: finding appropriate site and potentially long construction time, affected by the necessity of preparing the reservoir for the accumulation work and delivery of equipment – at least partially nonstandard and custom-designed.

3 Key features of the CAES plant

Technology of the compressed air energy storage plant is based on well-known solutions, which have been tested either in power industry or in gas industry. Those solutions are also well-known in Poland, at least on the operational level. Gas turbines used by the CAES solutions are based on adapted standard power solutions (extended with necessary elements). Compressor systems are based on solutions used in power installations (axial compressors) supplemented by elements tested in long-term operation in other branches of industry (centrifugal high-pressure air compressors).

Most studies on energy storage consider the CAES technology as the only alternative to the pumped-storage stations for the large power installations. The start-up time for a pumped-storage plant in the turbine mode is counted in minutes (from 1 to approximately 15). Start-up time of a CAES plant up to full load is two to three times shorter than the average for the classic gas turbine and is no higher than some 10 min.

Table 1. Estimated investment for the construction of a CAES plant [7,8].

Element	Rock storage	Salt cavern	Aquifer
Plant without the storage, $/kW	440	430	410
Storage, $/kWh	30	1	8
Storage time, h	10	10	10
Total cost, $/kW	740	440	490

The estimated data (for year 2000) presented in Tab. 1 (according to [7,8]) the expected cost of constructing a CAES plant is noticeably higher than for the classic gas turbine plant, but significantly lower (at least two times [4]) than for pumped-storage plants. Cost of a CAES plant stated in Tab. 1 can be considered comparable to expected in Polish conditions, where appropriate locations of underground storage suitable for air storage can be expected for instance in the area of Lower Silesia or Kuyavia. Constructing a CAES plant in Polish conditions could prove particularly attractive in coastal area, where it could cooperate with large off-shore wind farms.

The literature mentions two methods of underground air storage used in practice: constant pressure and constant volume. Alternative names for those solutions are wet and dry storage or air storage with and without compensation. In the constant volume technology the accumulator operates in the determined pressure range. The top pressure is defined by the geological conditions, primarily in reference to keeping leak proofness (determined by allowed air losses) during operation. The bottom pressure is defined by the allowed operational parameters of the plant's machinery fed from the accumulator. The accumulator's volume and mentioned pressures define the possible storage capacity.

4 Thermodynamic performance analysis

Comparison of different CAES plant variants can be done using the energy conversion efficiency defined as

$$\eta_{CAESc} = \frac{E_{e\,\mathrm{lg}}}{E_{elc} + Q_f}\ , \tag{1}$$

where E_{elg} and E_{elc} are electrical energy fed to the grid and consumed (to drive the compressor) by the CAES plant, respectively, Q_f is the chemical energy contained in supplied fuel.

Using the energy values (not power) is necessary to analyze the quality of energy conversion in the CAES system, because of different times of consuming and supplying electricity to the grid and different power values. The process parameters are variable in time, among them compressor capacity, dependent on the accumulator feeding pressure (if it is variable). The conditions inside the reservoir and process management (throttling, skid parameters, compressor stall limitations etc.) affect the time and regime of charging and discharging the accumulator. To determine those regimes it is necessary to construct appropriate dynamic model of the plant.

Using the efficiency definition (1) is not always convenient. We need to add up two different kinds of energy: electricity delivered by the grid and chemical energy supplied with the fuel. From this point of view it would be more appropriate to use the equation which includes the efficiency of electricity generation for the compression consumption

$$\eta_{CAESs} = \frac{E_{e\lg}}{\frac{E_{elc}}{\eta_{elR}\eta_{tr}} + Q_f} , \tag{2}$$

where η_{elR} is the electrical efficiency of a reference base load power station and η_{tr} is the efficiency of electricity transmission to the CAES plant. This method is an attempt to evaluate the consumption of the fuel energy necessary to generate whole electricity delivered from the CAES plant. In order to avoid necessity to add up two different kinds of energy (electricity and chemical energy) the efficiency of a CAES plant can be also defined as

$$\eta_{CAESf} = \frac{E_{e\lg} - E_{elc}}{Q_f} . \tag{3}$$

Considering the CAES technological process as a form of power generation based on delivered fuel. The efficiency defined in this way describes the effectiveness of fuel consumption in generation of net power output of the plant. It has to be emphasized, that the Eq. (3) can result in negative result (when $E_{elc}>E_{elg}$) or infinity (if $Q_f = 0$).

There is one more way to describe the efficiency of a CAES plant, used for instance in [9]. It is the net electrical storage efficiency, defined as the ratio of the electrical energy delivered to the grid over the energy supplied with the natural gas

$$\eta_s = \frac{1 - (HR\eta_{gas})}{ER_{net}} , \tag{4}$$

where HR is the gas turbine's heat rate, η_{gas} is the chemical energy to electricity conversion efficiency, and ER_{net} is the net supplied-received energy ratio. The result achieved from the Eq. (4) is sometimes given in balance sheets and compared to the efficiency of pumped-storage plants. For obvious reasons such a comparison is not unambiguous (see Fig. 11).

The process of charging and discharging the accumulator can be analysed with a mass and energy balances for the working medium (here transformed into the enthalpy balance):

$$\frac{dm}{dt} = \frac{d(\rho V)}{dt} = m_\alpha - m_\omega , \tag{5}$$

$$\frac{dH}{dt} = \frac{d(\rho V h)}{dt} = m_\alpha h_\alpha - m_\omega h_\omega + V\frac{dp}{dt} + Q , \tag{6}$$

where m is the mass flow, h and H are the enthalpy and total enthalpy, respectively, p is the pressure, Q is the exchanged heat, ρ is the density, V is the volume, and t is the time; α and ω indexes mark appropriate parameters on inlet and outlet from the modeled accumulator (reservoir). In the extended form these equations are sometimes transformed based on (not always explicit) ideal gas model assumed for the working medium. Because of high pressure and significant pressure differences in the process this is a significant simplification. The specific heat in the room temperature changes by some 18% in the pressure range from 1 to 100 bar, so also the isentropic exponent is variable.

Equations (5) and (6) should be analyzed separately for charging and discharging modes. The work (energy consumption) needed to compress the working medium in the charging process has to be determined. Analogically the work of the turbine expansion process can be calculated. The analysis has to take into account processes of cooling the working agent between the compressor stages and after the compressor as well as the work received from the turbine.

5 Results of charging and discharging simulations

The premises and calculation results obtained for a CAES plant model with air expansion (combustion chamber simulated as the air heater) are presented below. The model was created in the HYSYS software environment used as a tool to generate dynamic characteristics. The performance characteristics (including the efficiency defined according to formulas (2) and (3)) of the CAES plant for various operational parameters can be found in the study [10] or – for a bit different installation – in [11].

Main premises for calculations:

- Capacity of the air accumulator (cavern) – 300,000 m^3 – constant volume system
- Heat and air losses to the environment considered negligible
- compressor polytropic efficiency: 75%
- compressor power: 60 MW
- turbine polytropic efficiency: 75%
- nominal air flow through the turbine: 400 kg/s
- turbine outlet pressure: 1 bar
- working medium model (Peng Robinson equation of the state)

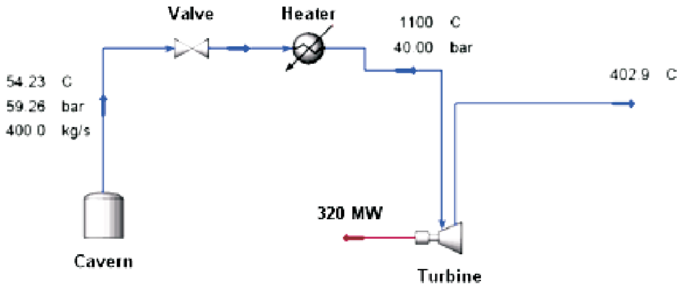

Figure 4. Scheme of the cavern discharging process in the software used.

Individual elements constructed in the HYSYS software environment create a dynamic model of the compressor unit (Fig. 3) and turbine unit powered by the air from the same cavern (Fig. 4). The assumed nominal parameters of the turbine were:

- inlet pressure: 4 MPa
- outlet pressure: 0.1 MPa
- working medium (air) mass flow: 400 kg/s.

The calculation results presented below refer to the following selected cases:

- charging the cavern from the pressure of 1 bar (50 °C) to 70 bar in the system fitted with inter-cooler and after-cooler (50 °C/50 °C),
- discharging from 70 bar (50 °C) to 1 bar with additional heating the air to the temperature of 1100 °C and throttling the agent before the turbine to 40 bar.

The charts present characteristics of the compressor-cavern (Figs. 7, 8, 9) and cavern-turbine (Figs. 8, 9, 10) subsystems. Figure 5 illustrates the accumulation capacity of the cavern with respect to the stored energy and air mass, while Fig. 6 presents changes in time of the air flow into the cavern and increase in cavern pressure. The power consumption of the compressor, air temperatures after the HP part and temperatures of the stored air shows Fig. 7. Real operation of CAES plant is carried out within the narrower pressure range than investigated here. The bottom pressure is selected so the plant has a reserve air for possible emergency start-up. For instance Huntorf Power Station is operated within the

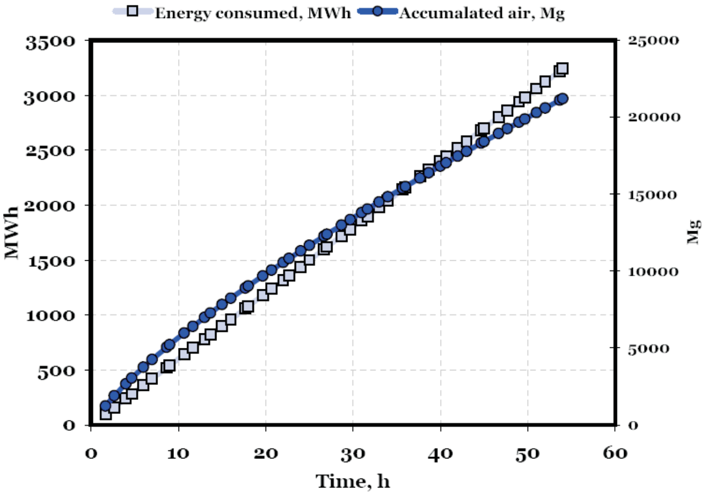

Figure 5. Mass of the air accumulated in the cavern and the energy consumed by the compressor during the charging process from the 0.1 MPa to 7 MPa; compressor with a single-stage inter-cooler and after-cooler.

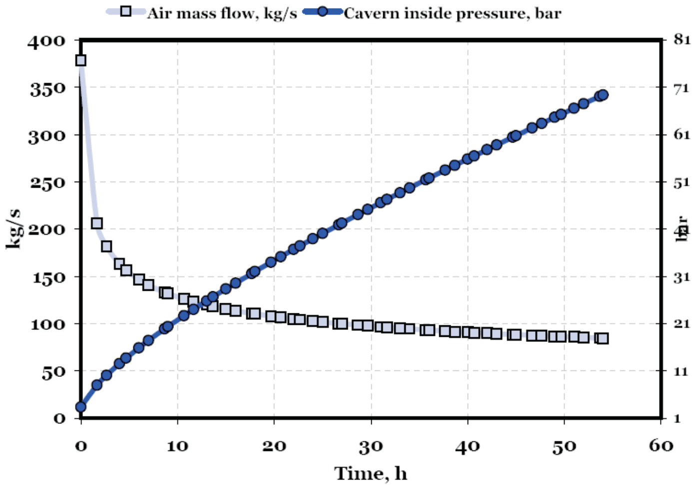

Figure 6. Mass flow of the air fed into the cavern and the cavern pressure during the charging process from the 0.1 MPa to 7 MPa; compressor with a single-stage inter-cooler and after-cooler.

pressure range of 4.3–7 MPa. In extraordinary situations it is allowed to decrease the operational pressure to 2 MPa. Analysis of the impact of the bottom air pressure on the performance of the CAES plant was carried out in [10].

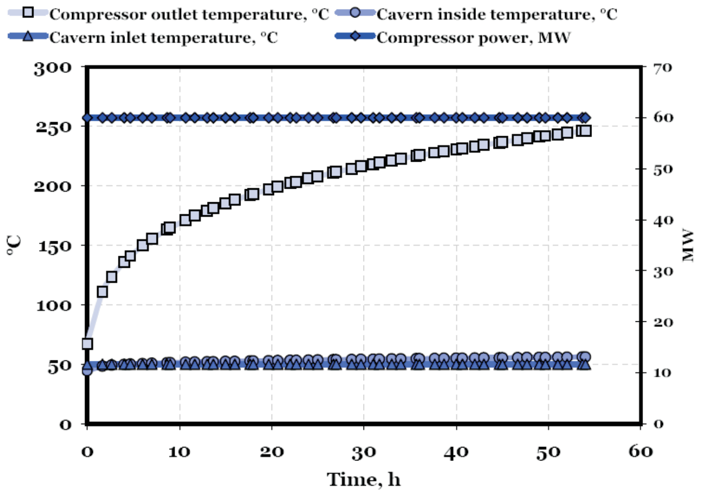

Figure 7. Air temperature after the compressor and in the cavern during the charging process from the 0.1 MPa to 7 MPa; compressor with a single-stage inter-cooler and after-cooler.

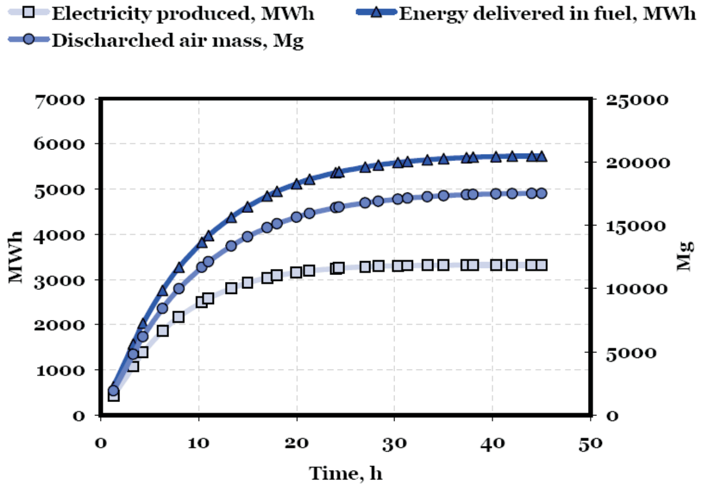

Figure 8. Mass of the air discharged from the cavern and the energy delivered in fuel during the discharging process from 7 MPa to the ambient pressure with the air heated to 1100 °C before the turbine.

The power output on the generator terminals, at the premises mentioned above, is 320 MW and can be attained for almost 7 h. After this period it decreases, so the half of the maximum output can be generated for next 5 h (Fig. 10). The turbine inlet pressure is kept at constant level of 4 MPa as long as

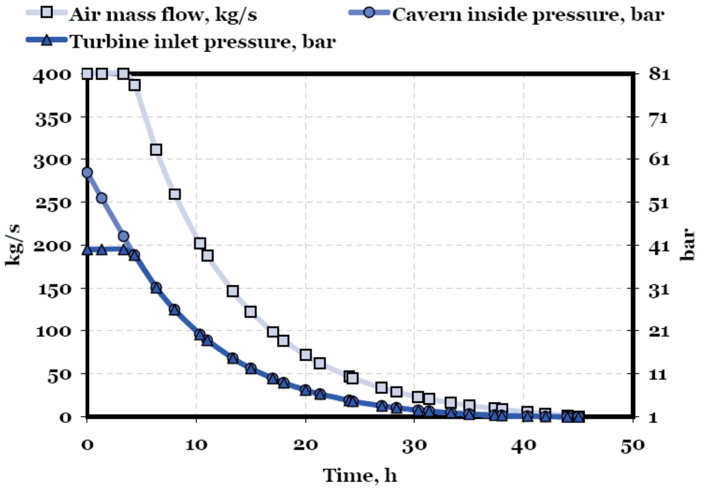

Figure 9. Mass flow of the air discharged from the cavern, cavern pressure and turbine inlet pressure during the discharging process from 7 MPa to the ambient pressure with the air heated to 1100 °C before the turbine.

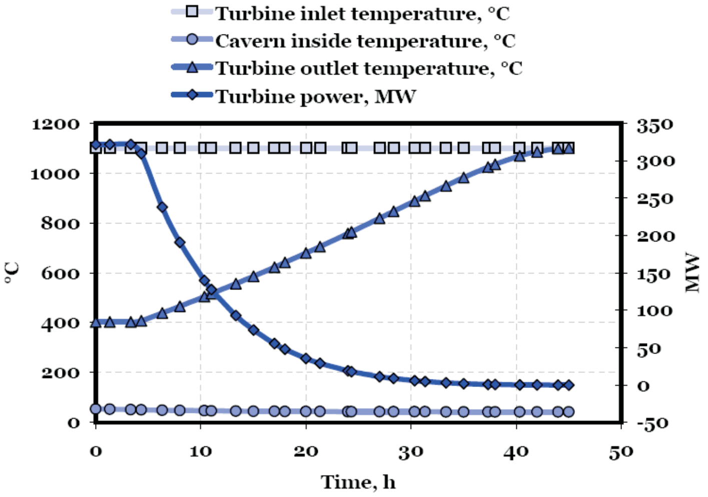

Figure 10. Turbine power output, turbine inlet and outlet temperatures and cavern temperature during the discharging process from 7 MPa to the ambient pressure with the air heated to 1100 °C before the turbine

the cavern pressure is higher. During the further stage of discharging the turbine inlet pressure decreases along with the cavern pressure (Fig. 9). The energy is produced by the turbine is at the cost of discharging the air accumulator and fuel gas combustion (Fig. 8.)

6 Conclusions

Introduction of the emission trading scheme for the greenhouse gases, primarily the carbon dioxide, increases price competitiveness of the power generated by renewable technologies (RT). Significant drawback of the RTs however is irregularity of their power output. Introduction of the storage capability in a cooperating CAES plant allows eliminating this disadvantage, and if the purely adiabatic method is used, it keeps the greenhouse gas emission at the zero level. Generated electricity becomes dispatchable and can be used to cover the peak load. If the additional organic fuel (for instance natural gas) combustion is used in the discharged air flow, the combined system of cooperating Renewable-CAES plant still displays emission levels much lower than a standard gas-fired plant. Full independence from the variability of renewable power generation is provided by introduction of supplementary supply of fuel gas to such a plant. Zero emission level could be achieved if this gas fuel was a renewable one (biogas). Such concepts are also considered.

In case of a plant using additional fossil fuel in Polish conditions it has to be pointed out, that due to formal regulations some (or all) green certificates for the CAES-generated electricity could be lost. This issue greatly influences the energy sales price. The authors have not analyzed this question in detail, though it is a crucial factor, which might decide the feasibility of a possible investment.

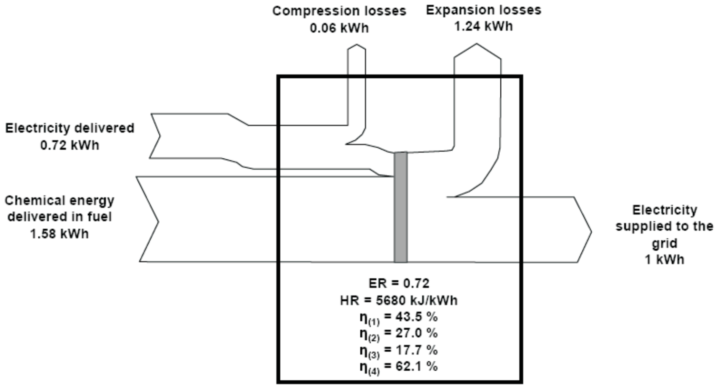

Figure 11. Sankey's diagram of energy flows during charging and discharging processes.

The CAES plant displays good characteristics for partial-load operations. This is its significant advantage over the classic gas turbine plants. It can also achieve very fast turbine load changes of several dozen percent in a minute. Those capabilities make the system suitable for the peaking operation in a role of a fast reserve, for grid stability services and reactive power compensation.

In Poland there are potential sites suitable to construct the compressed air energy storage plants, for instance salt caverns. Especially nowadays construction of such a plant might prove interesting, bearing in mind large investments in wind power – already started or planned in the imminent future, primarily in the northern part of the country.

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References

[1] Crotogino F., Mohmeyer K.-U., Scharf R.: *Huntorf caes: More than 20 years of succesful operation*. In: Proc. Spring 2001 Meeting, Orlando, Florida, USA.

[2] Crotogino F.: *Druckluftspeicher – Gasturbinen – Kraftwerke Geplanter Einsatz beim Ausgleich fluktuierender Windenergie – Produktion und aktuellem Strombedarf*. In: Proc. Kasseler Symposium Energie – Systemtechnik ISET, 2002.

[3] *Review of electrical energy storage technologies and systems and of their potential for the UK*. Techn. Rep.: Contract No. DG/DTI/00055/00/00 URN No. 04/1876, EA Technology, 2004.

[4] Badyda K., Milewski J.: *Revies of air and gas turbine applications to energy storage in power installations*. Techn. Rep., Fundacja Energetyka dla Siebie Przyszłości, Warsaw 2005.

[5] Szabłowski Ł., Milewski J.: *Dynamic analysis of compressed air energy storage in the car*. J. Power Technologies **91**(2011), 1, 23–36.

[6] Haug B.: *The Iowa stored energy plant*. Techn. Rep., DOE Energy Storage Systems Program Annular Peer Review, 2004.

[7] Bradshaw D.: *Evaluation of sub-surface compressed air energy storage (SSCAES) for energy storage*. In: Proc. ESA Meeting for Energy Storage 2000.

[8] Bradshaw D.: *Pumped hydroelectric storage (PHS) and compressed air energy storage*. In: Proc. ESA Meeting for Energy Storage 2000.

[9] Denholm P., Kulcinski G.L.: *Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems*. Energy Conversion and Management **45**(2004), 2153–2172.

[10] Skorek J., Banasiak K.: *Thermodynamic analysis of the compressed air energy storage system 2003*. In: Proc. the 9th Int. Conf. Thermal Energy Storage Futurestock, 179–184. Warsaw 2003.

[11] Najjar Y., Zaamout M.: *Performance analysis of compressed air energy storage (CAES) plant for dry regions*. Energy Conversion and Management **39**(1998), 15, 1503–1511.

Analiza termodynamiczna pracy układu *CAES*

Streszczenie

Przedstawiono technologię CAES (ang. *compressed air energy storage*) oraz możliwości generowania energii elektrycznej z jej udziałem. Pokazano główne parametry eksploatacyjne oraz możliwe tutaj do zastosowania definicje sprawności takich układów. Występują tutaj możliwości budowy układów hybrydowych CAES + technologie odnawialne, takie jak np. elektrownie wiatrowe. Zaproponowano potencjalne lokalizacje takich hybrydowych rozwiązań. Wyniki obliczeń oparto o model dynamiczny układu CAES – ładowanie i rozładowanie kawerny.